CUDOS

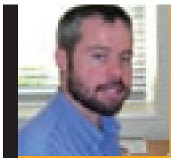
Optical Devices and Applications Program

Annual Report 2004

The Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS)

An Australian Research Council Centre of Excellence

Optical Devices and Applications Program



Program Manager: Ben Eggleton

Program Overview

The objectives of this program are to develop novel photonics devices for optical signal processing. During 2004 we made significant advances by demonstrating:

- **all-optical wavelength conversion with low noise and ripple,**
- **all-optical monitoring of two key network parameters of optical performance, the optical signal to noise ratio and dispersion,**
- **all-optical signal regeneration and re-amplification**

We also made progress towards our ultimate goal of producing optical systems in which these effects occur on a sub-millimetre scale ("microphotonics"), by developing three platform technologies:

- **Photonic nanowires, produced by careful tapering of microstructured optical fibres with a "grapefruit" cross-section, exhibiting low loss optical propagation**
- **Bragg gratings in a silicon rib waveguide, produced using focused ion beam etching**
- **Ultra strong Bragg gratings in a chalcogenide rib waveguide, produced using an interferometric laser writing technique**

The activities in the program are organised into three projects all headquartered at Sydney University, but the program is characterised by strong collaborations across all nodes.

Nonlinear optical waveguide devices and applications project

Project Leader: Justin Blows

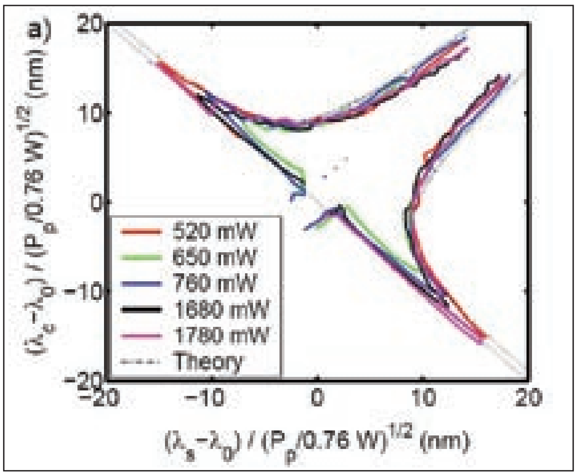
Justine Blows

The project spans activities at Sydney, Macquarie and Australian National Universities. The aim is to demonstrate and develop key all-optical signal processing functions such as regeneration, wavelength conversion and amplification, which are crucial for the next generation of optical telecommunications systems. We aim to realise these functions using the cubic non-linearity of glasses and the Raman scattering effect.

Fibre tunable wavelength converter

McKerracher, Blows, de Sterke

We experimentally demonstrated wavelength conversion over a wide bandwidth using parametric amplification. Experiments confirmed theory that we developed in 2003, predicting the optimal fibre parameters used to achieve high conversion efficiencies. Experiments confirmed the device adds little noise to the signal, a considerable advantage over the other potential wavelength conversion technologies. We commenced a theoretical and experimental investigation of pulse propagation through these devices using pulses typical of 160 Gbit/s systems.



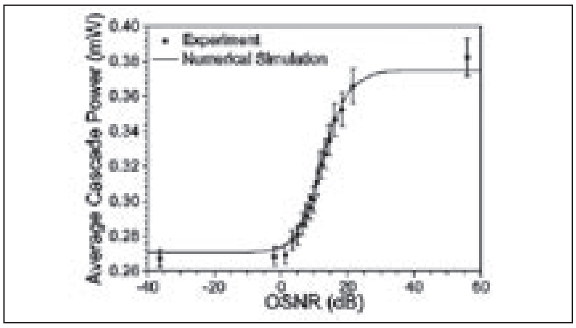
Experimentally obtained contour plots of equal conversion efficiency for the parametric wavelength converter investigated by McKerracker et al. Up to 24 nm of bandwidth has been obtained, and the agreement with theory is excellent.

Optical signal-to-noise ratio monitoring with gain and frequency conversion

Ng, Blows, Eggleton

We demonstrated a wavelength converter with gain that also measures the optical signal-to-noise ratio (OSNR). If the OSNR drops, for example because of noise in optical amplifiers, the bit error rate of the network will increase. Measurement of OSNR at multiple locations enables noise sources to be identified and corrected. Our technique measures in-band OSNR without requiring interpolation of amplified spontaneous emission levels into the band.

This all-optical replacement of two electronic devices processes higher data rates and offers scope for even greater integrated functionality. Demonstration of this all-optical integrated functionality exemplifies the CUDOS mission.



▲ **Nonlinear interactions in optical fibre demonstrate strong correlation with OSNR in real time, and will be useful in monitoring future ultrafast networks.**

All-optical monitoring of polarisation mode dispersion

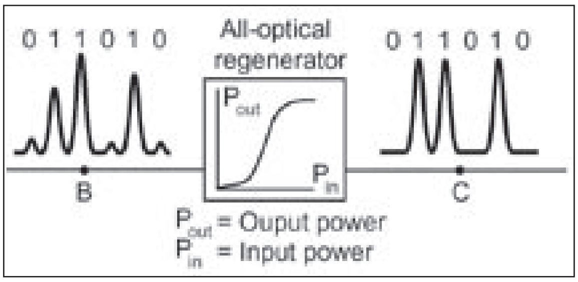
Blows, Hu, Moss, Luther-Davies

Using all-optical fiber nonlinear optics we successfully measured for the first time the effects of polarisation mode dispersion on ultrafast signals. Because linear degradation mechanisms such as group velocity dispersion and polarisation mode dispersion change the power spectrum of the optical signal in characteristic ways, we can use that information for dynamic correction of dispersion.

All-optical regeneration

Mok, Rochette, Blows, Eggleton, Kutz, Moss

All optical regeneration restores pulses degraded during transport without resorting to electronics. Optical systems will replace electronic ones as networks evolve towards dynamic routing and increased transparency. We modelled pulse regeneration using nonlinear optics, including the "Mamyshev" and "Parametric amplifier" regenerators to show that different regenerators behave quite differently for different degradation mechanisms. We also discovered that the "Mamychev" regenerator has a unique ability to actually recover information that would otherwise be lost to noise.



▲ **Research in all-optical regeneration, by Mok et al., have shown that regenerators can recover severely corrupted data.**

High speed pulse generation

Bolger, Hu, Mok, Blows, and Eggleton

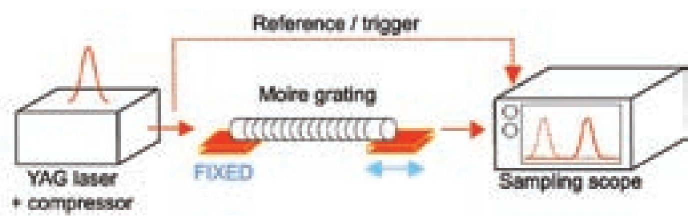
Ultrafast networks require a source of short pulses at a high repetition rate. However, this type of source has been difficult to build. We demonstrated a way to multiply the repetition rate of a laser to useful levels; this enables the application of a laser with short pulses, but a slow repetition rate, to ultrafast networks.

Optical buffering via slow light in Moiré fibre Bragg gratings

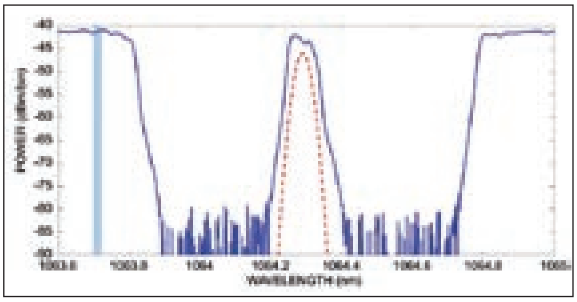
Mok, Littler, Eggleton

An all-optical processor requires an "optical buffer" in applications such as packet synchronisation in telecommunication networks, or optical buffering in quantum computing. One approach to an optical buffer is based on the dramatic "slowing" of light that should occur in optical media at wavelengths close to spectral features where the refractive index varies rapidly – absorption lines, band-edges etc. Demonstrations of this effect in atomic systems like Bose Einstein Condensates show large delays but over extremely narrow bandwidths. We investigated novel approaches that enable substantial delays to be achieved over much wider bandwidths, making them suitable for application to ultrashort pulses.

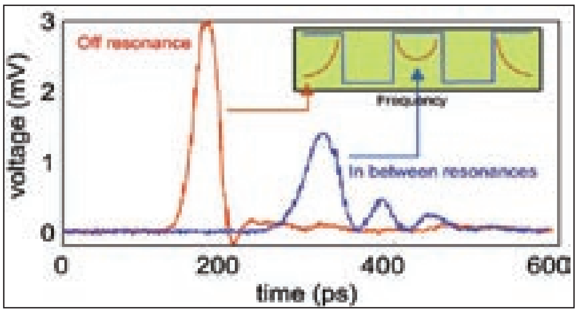
An optical pulse launched into a fibre Bragg grating near the edges of its photonic bandgap will be transmitted with a delay but suffers from dispersion. However, when launched between the two adjacent bandgaps of a Moiré fibre Bragg grating the delayed 30 ps pulse experiences zero group velocity dispersion but is delayed by 150 ps in a Moiré fibre Bragg grating. The trailing oscillation in the delayed pulse is due to higher order dispersion terms.



▲ **Experimental setup for slow light.**



▲ **Measured transmission spectrum of the Moiré fibre Bragg grating compared to the input pulse spectrum.**

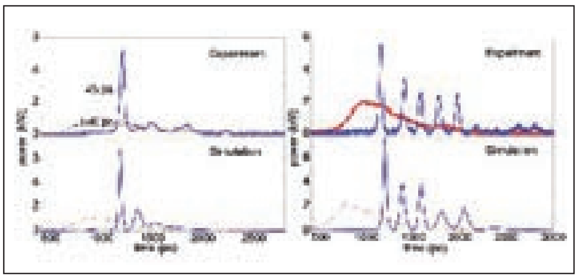


▲ **Pulse delay measurement, showing slowing of light near the edge of the photonic bandgap.**

Photonic bandgap solitons

Mok, Littler, Tsoy, Eggleton

Photonic crystal structures such as fibre Bragg gratings have a large range of dispersion over a narrow band, and can therefore be easily reconfigured to transform an optical signal. For instance, high intensity pulses launched into a fibre Bragg grating experience both extremely high dispersion and enhanced nonlinearity. The interaction between dispersion and nonlinearity results in pulse shaping effects including soliton pulse compression and pulse train generation via modulation instability. A 12-fold pulse compression of a 580 ps pulse to 45 ps pulse width with five times peak power enhancement was obtained in a 100 mm long fibre grating. Modulation instability in the same fibre grating can lead to pulse train generation.



▲ **(Left) Pulse compression in a bragg grating and (Right) Pulse train generation via modulational instability.**

Microstructured Optical Fibres

Project leader: Ross McPhedran

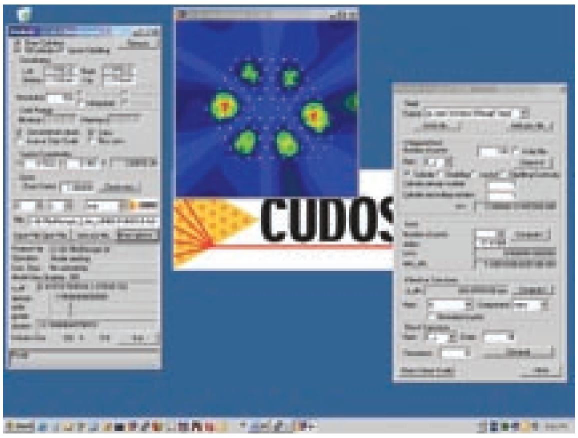
Justine Blows

Microstructured optical fibres (MOFs) can be used for a range of photonic functions. In this project we combine activities in sophisticated analytical and numerical modeling with experimental investigations to develop novel MOF designs and applications. Design examples include our studies of anti-resonant reflecting optical waveguides (ARROW), while applications include photonic nano-wires, sensors, optical switches and tunable filters. In our experimental program we have developed two powerful techniques that have underpinned a number of successful projects: MOF tapering, where the microstructure is preserved as the fibre is tapered down by factors of ten or more in the diameter, and transverse probing, in which the fibre microstructure forms a semi-infinite two dimensional photonic crystal for light travelling across the fibre. The resulting modification in the spectrum and direction of light propagation has been exploited to create a rich range of exciting experimental demonstrations of novel photonic switches and spectral filters. The project is based at Sydney, and has strong collaborations across all nodes, especially with UTS and Swinburne University. The results of international collaborations with the Institut Fresnel (Marseille, France) and OFS Laboratories (New Jersey, USA) are also reported here.

CUDOS MOF Utilities

Kuhlmey, McPhedran, Campbell

Modelling the propagation modes in MOFs underpins all research activities in this area. We have developed a powerful software suite for this purpose, operating in the Windows environment, which was placed on the CUDOS website in April 2004. The software enables the fast and accurate modeling of MOFs composed of circular air holes in silica or other materials. The figure shows a screenshot of the CUDOS MOF Utilities field visualisation tool. The software has met with extraordinarily strong interest from the entire community of MOF users, with more than 400 downloads occurring from research groups in 44 countries. There is also an in-house version of the utilities, which gives researchers within CUDOS access to important extra functionalities compared with the public version.

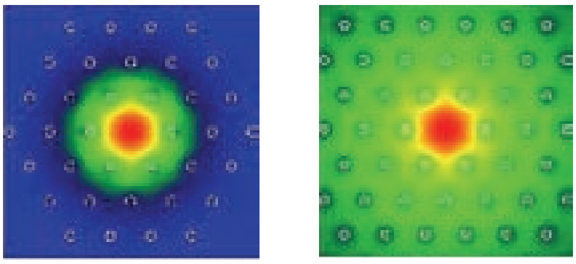


▲ **User interface for CUDOS MOF utilities.**

MOFs modelled as defects in truly infinite structures

McPhedran, Wilcox, de Sterke, Botten, Kuhlmey

We have answered an important question for the practical applications of MOFs. What is the range of geometries and wavelengths for which they can be regarded as single moded? We published results in 2002 which we interpreted to show that there was only a limited region of wavelengths for any MOF in which its fundamental mode could be regarded as guided. This work was questioned by the pre-eminent group at the University of Bath, and in consequence we developed an entirely new method capable of investigating the modal properties of a single defect in an infinite photonic crystal. The method combines fictitious sources to eliminate reflections from a periodic line of cylinders, with superposition to get rid of those sources on all but one cylinder. It has given results which



▲ **Power distribution of the fundamental mode in MOFs of finite (left) and infinite (right) cross-sections, at the same wavelength in the extended mode region. In the finite case, the mode is confined by the holey region's external boundary but is extremely lossy. In the infinite case the mode is lossless, but spreads far into the cladding.**

showed that indeed the fundamental mode is never cut-off, but for long wavelengths it becomes so weakly confined as to be useless in practical applications.

ARROW fibres

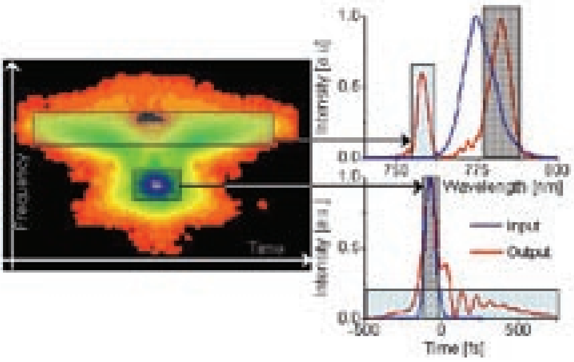
Steinvurzel, Eggleton, Steel, White, McPhedran, de Sterke, Kuhlmey

Photonic crystal fibers (PCFs) consisting of an array of high index rods in a low index matrix, with a missing rod defect forming the core, are fundamentally different from conventional air hole PCFs. They do not guide light through coherent Bragg scattering from the photonic crystal cladding, rather guidance in the core is driven by anti-resonant backscattering from the high index rods. The modal properties of these Anti-Resonant Optical Waveguides (ARROW) depend strongly on the index and size of the rods, but only weakly depend on their geometric arrangement. However, there was some ambiguity as to the validity of this model at long wavelengths comparable to the size of the PCF microstructure features. We numerically and experimentally investigated long wavelength transmission in an anti-resonant PCF and verified the anti-resonant model to first order. This was the first published experimental confirmation of the anti-resonant PCF model at any wavelength.

Nonlinear pulse propagation in ARROW-PCFs

Fuerbach, Steinvurzel, Bolger, Nulsen, Eggleton

The guidance in the core of an ARROW fibre is based on a resonant process rather than conventional total internal reflection, so these fibres have discrete transmission bands and exhibit very strong waveguide dispersion. We created ARROWs in photonic crystal fibres by filling the air holes with



▲ **Pulse propagation in ARROW fibre at zero dispersion.**

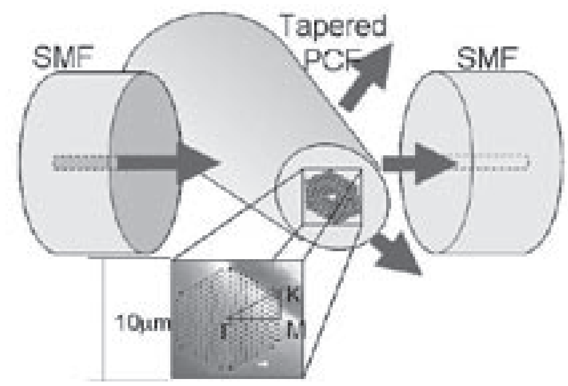
a high index fluid. By appropriately choosing the index of the fluid, we can tailor the dispersion at a given wavelength.

With this flexibility in dispersion engineering we studied the evolution of femtosecond pulses in ARROW fibres for the cases where nonlinearity and dispersion act together to broaden the pulse in time (normal dispersion) or offset each other so that the pulse does not change at it propagates (anomalous dispersion); the latter is an example of a solitary wave, or soliton. We also performed a detailed analysis of pulse propagation at zero dispersion, where the pulse splits into two components consisting of a soliton and a dispersive wave, as shown in the accompanying figure.

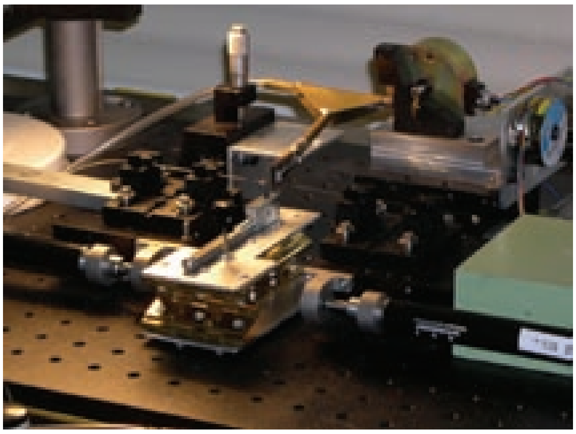
Transverse probing

Magi, Nguyen, Domachuk, Smith, Steel, Chapman, Grillet, Eggleton

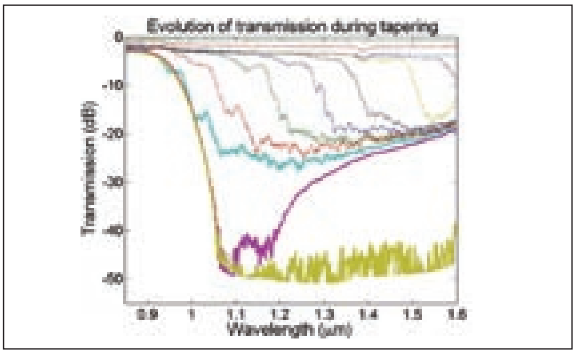
Since the first demonstrations of transverse probing of MOF's, the technique has become a valuable tool for both optical device fabrication and as a measurement tool to characterise photonic crystal fibres and tapers. We have now developed, tested and calibrated a method to infer pitch within the microstructure of a MOF from transverse transmission measurement. This is a useful tool for optimisation of MOF tapering (discussed on the next page).



▲ **Basic transverse probing geometry.**



▲ **Fibre taper rig with flame brushing in progress.**



▲ **Graph showing shift of transmission spectrum to shorter wavelengths as fibre is tapered.**

In 2004, a number of projects utilised transverse probing. These included the formation of tunable microfluidic Mach Zehnder interferometric switches, tunable microfluidic PCF switches and the characterisation of adiabatically tapered photonic crystal fibres.

Microfluidics

Domachuk, Grillet, Chapman, Eggleton, Cooper-White (University of Queensland)

We are developing a program to use microfluid "slugs" inside the capillaries of MOFs to alter the optical characteristics of these fibres both for propagation along and transverse to the fibre axis. A highlight of work in the area was the demonstration of a microfluidic Mach-Zender switch in hollow core fibre. Light travelling across the core suffers a differential phase shift between one side of the beam and the other as the meniscus of a microfluid plug, moving through the hollow core, partially intercepts the beam. The differential phase shift leads to a spectrally-dependent intensity change which depends upon the position of the meniscus, its shape and the refractive index of the fluid. Ideally the meniscus should be flat, and with collaborative support A/Professor Cooper-White at the University of Queensland we achieved this through chemical surface processing. We are now extending this work to produce more sophisticated switchable optical filters by selective filling of holes in a microstructured fibre.

MOF Tapers

Magi, Nguyen, Smith, Steinwurzel, Steel, Eggleton, McPhedran, Kuhlmey

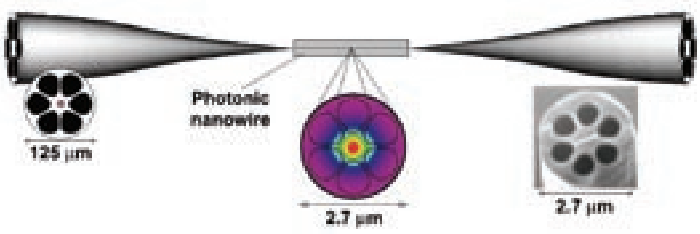
In 2004 we developed a second taper rig facility that can draw longer tapers at faster rates with improved computer interface and control. This allowed the production of adiabatic photonic crystal fibre tapers for a range of applications. One example is for improved MOF mode field converters to couple light in and out of the chalcogenide planar waveguides under development by Dr Moss and Professor Luther-Davies.

More generally, the tapering of MOFs offers us the ability to further enhance and engineer their waveguiding properties. Experiments to develop a range of applications (couplers, sensors, nanowires etc) have been complemented by fundamental studies of mode propagation in tapered microstructured fibres. In these studies, we observe a striking long-wavelength loss transition, which shifts to shorter wavelengths as the PCFs are tapered to smaller dimensions. Through theoretical modelling, we associated this sharp loss-transition with the leakage of the fundamental core mode, identified previously as the cutoff of the mode associated with finite-micro structured PCFs.

Nanowires

Nguyen, Magi, Lize, Ta'eed, Bolger, Eggleton

Sub-micron diameter fibres were produced by tapering both SMF28 and Grapefruit micro-structured fibres. We were able to produce tapers having widths as small as 200 nm. It was found however, that the micro-structures in the grapefruit fibre collapsed for taper width dimensions below 1 μm. Two propagation regimes were identified. These were the "embedded" regime, where the mode is confined within the solid core and is shielded from the external environment, and the "evanescent" regime where a significant portion of the light is external to the air glass boundary. Calculations also showed that the nonlinear effect is optimum just prior to the transition from embedded to evanescent regimes which corresponds to the peak field intensity within the solid core. These results open up a range of exciting applications: in the embedded regime the fibre acts as a "nanowire" for low loss transport of photons, while in the evanescent regime the taper can act as an environmental sensor.

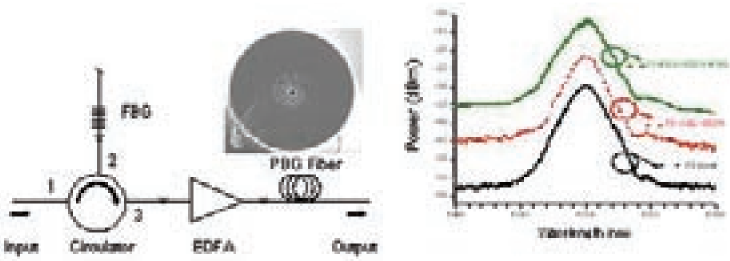


▲ **Efficient coupling into nanowires: the mode in a grapefruit fibre is adiabatically coupled into a section where the mode field diameter is less than 1 µm.**

Multi-kilowatt, all-fibre chirped pulse amplification system employing photonic bandgap fibres

Fu, Littler, Eggleton

Photonic bandgap fibre is an ideal medium for the compression of high power pulses. With dispersion nearly one thousand times that of standard single mode fibre and reduced nonlinearity because of the large air fill fraction compared to index guiding fibres, an optical pulse can be "stretched", amplified and re-compressed to recover the original pulse shape to a high degree of accuracy. By using a specially designed fibre Bragg grating to match both the linear and cubic dispersion terms of photonic bandgap fibre we can create a compact, in-fibre chirped pulse amplifier in which the amplified, recompressed pulse is close to transform limited.



▲ **Experimental set up for pulse stretch amplifier (left). Output spectrum (right).**

A scalable, all in-fibre pulse stretch amplification scheme was demonstrated which exploits these properties of a photonic bandgap fibre. A preamplifier pulse stretch stage, which exactly matches the nonlinear dispersion terms of the photonic bandgap section, reduces the pulse intensity and avoids self phase modulation, allowing nearly perfect pulse recompression. This system requires no daily realignment and is contained in a package with a foot print of around 100 cm^2. A peak power of 2.3 kW was achieved in a pulse with duration as short as 1.47 ps. Furthermore, there was no self phase modulation in the amplifier or in the fibre as demonstrated by the spectrum in the figure.

An all in fibre amplification system of this kind has wide application in nonlinear based communication sub-systems based on silica and chalcogenide waveguides, as well as in supercontinuum generation, frequency doubling, spectroscopy, biology and laser micro-machining.

Modelling chalogenide fibres

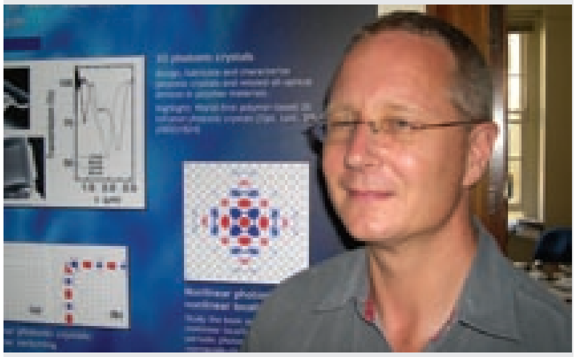
Kuhlmey, Renversez (Institut Fresnel, Marseille)

Arguably, the most striking property of solid core MOFs is that they can be endlessly single-mode. In conventional step index fibers, the number of guided modes increases with decreasing wavelength, and it is only at wavelengths longer than the cutoff wavelength that the fiber is single-mode. In contrast, infinite solid core MOFs can remain single mode at all wavelengths if the holes are sufficiently small.

Previous studies of the second mode cutoff in MOFs have led to a phase diagram which partitions the parameter space into three regions, depending on whether the is single-mode, multimode or endlessly single mode. However, this phase diagram was established solely for silica MOFs. We studied the effect of the MOF's background refractive index on the phase diagram and accurately determined the critical relative hole size delimiting the endlessly single-mode region and found that it is independent of that background index.

Photonic Integrated Circuits and Planar Waveguides Project

Project Leader: David Moss



This project is aimed at experimental demonstrations of novel photonic integrated circuits (PICs) in a number of material systems for operation both as linear devices (2D photonic crystal and photonic crystal waveguides) and nonlinear devices. Linear devices that we are investigating include 2D photonic crystals, "defect" PC waveguides, defect resonant cavities, and 1D waveguide grating filters.

Nonlinear devices that we are studying primarily focus around exploiting the nonlinear refractive index n_2. Our goal is to achieve a range of ultrafast nonlinear all-optical signal processing functions through self-phase modulation, cross-phase modulation, Raman gain and two-photon absorption. Optical processing functions under study are all-optical signal regeneration, optical performance monitoring, demultiplexing and wavelength conversion. We are investigating several material systems including chalcogenide glass and silicon-on-insulator. The work builds on strong collaboration between the experimental team at Sydney and the group of Professor Luther-Davies at ANU. We are also establishing strong links with the Canadian Photonics Fabrication Centre at the National Research Council of Canada in Ottawa.

David Moss

Semiconductor Photonic Integrated Circuits

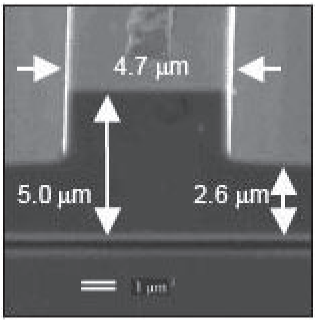
Ta'eed, Grillet, Fu, Moss, Eggleton, Luther-Davies, Ruan

We developed processes for building compact photonic structures that demonstrate nonlinear optical behaviour, leading to applications in areas such as optical performance monitoring and signal regeneration. We developed ridge waveguide devices for nonlinear optics and 2D photonic crystal devices for linear optical propagation and (eventually) nonlinear optical processing.

Good progress during 2004 was made on rib waveguide fabrication. We used photolithography and reactive ion etching to produce silicon on insulator rib waveguides and then wrote surface relief waveguide gratings into the waveguide by focussed ion beam milling. Waveguide gratings are a key component for future nonlinear waveguide devices for their linear filtering properties including both reflection/transmission spectra and dispersion characteristics.

In the course of the project we discovered some very interesting and novel features of shallow surface gratings in very high index waveguides. These gratings can greatly enhance the interaction with very high order leaky modes relative to the fundamental mode. This potentially has applications for devices whose operation depends on control of the higher order modes (both linear and nonlinear).

New devices are currently being fabricated at the National Research Council Canada in Ottawa to produce much smaller waveguide dimensions (1.5 x 1.5 □m). In addition, waveguide gratings fabricated by electron beam lithography and ICP etching are being fabricated. Both of these approaches are expected to yield very deep grating structures in waveguides with much fewer higher order modes and much stronger fundamental peaks more appropriate for applications in nonlinear optical regenerators.



Cross section SEM of an SOI rib waveguide used for fabricating waveguide gratings.

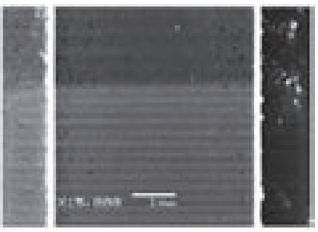
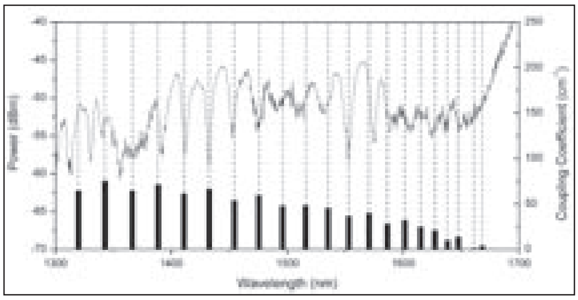


Image of FIB surface grating.



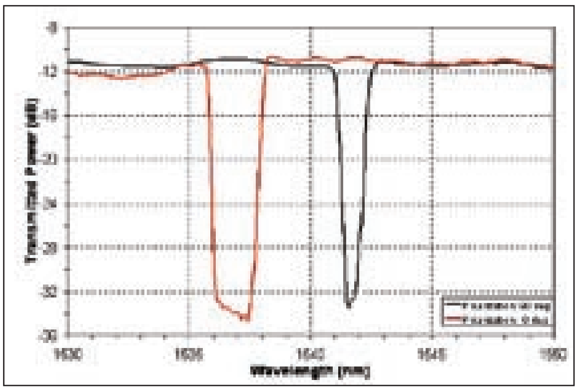
Optical Transmission spectrum from surface waveguide grating in SOI waveguide fabricated by focused ion beam milling (FIB), along with theoretical calculations of the grating peak wavelengths and strengths.

CPFC Building, adjacent to the Institute for Microstructural Sciences at the National Research Council of Canada in Ottawa, Canada.

Sub-Project Chalcogenide Waveguide Gratings

Ta'eed, Shokooh-Saremi, Littler, Moss, Eggleton, Luther-Davies, Ruan

We have taken an important step in the development of all-optical photonic integrated circuits (PICs) by successfully writing gratings in As_2S_3 chalcogenide waveguides using 532 nm light in a Sagnac interferometer configuration. The gratings were 5 mm long and were self-apodized. Gratings were fabricated with bandwidth greater than 5 nm wide and with measured rejection more than 30 dB rejection. The actual grating strength is probably greater than 40 dB. These are the strongest gratings reported to date in chalcogenide waveguides.



Transmission spectra for photosensitive gratings written in chalcogenide waveguides. The two curves are for two orthogonal polarisations. The grating strength of 22 dB is limited by measurement.